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Estimation of carbon pool in soil, above and below ground vegetation at different types of mangrove forests in Peninsular Malaysia

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ABSTRACT

This paper evaluated the total carbon stock of mangrove ecosystems in two contrasting sites: a fishing village in Delta Kelantan (DK) and Ramsar sites in Johor Park (JP). In both sites, aboveground carbon was significantly higher than belowground carbon, and stems contained more carbon than leaf and root partitions. The average carbon concentration of individual mangrove species (44.9–48.1%) was not significantly different but the larger biomass of the DK samples resulted in vegetation carbon stock that was higher than that in JP. Season played an important role in soil carbon stock—a pronounced wet season in DK coincided with the dry season in JP. The total carbon pool was estimated to be 427.88 t ha^{-1} in JP and 512.51 t ha^{-1} in DK, where at least 80% was contributed by soil carbon. The carbon dioxide equivalent was 1570.32 t ha^{-1} CO_2e (JP) and 1880.91 t ha^{-1} CO_2e (DK).

1. Introduction

Four countries (Indonesia, Brazil, Australia and Mexico) account for about 42% of all mangroves, and 64% of the total mangrove area is found in just 10 countries (Giri et al., 2011). Southeast Asian mangroves are the best developed and probably the most species-diverse in the world (Giesen et al., 2007). Yet, carbon studies on mangroves are limited. The carbon studies of mangrove and ocean ecosystems are known as blue carbon studies (McLeod et al., 2011). According to Herr et al. (2012) 'blue carbon' is carbon stored, sequestered or released from vegetated coastal ecosystems such as tidal marshes, mangroves and sea grass meadows, while Pendleton et al. (2012) refers to 'blue carbon' as mangrove forests, sea grass meadows, tidal marshes—vegetated coastal ecosystems that represent significant carbon stocks. Despite that, coastal vegetation continues to disappear and degrade as a result of continuing development pressures.

Blue carbon studies are crucial to understand global warming issues. According to Sinha (2005), global warming is described as the observed and projected increase in globally averaged temperatures over time and a dynamic system, which means it has occurred in the past and will continue to occur in the future. The concentration of carbon dioxide (CO_2) has increased markedly at a rate of 2.0 ppm/year from 2000 to 2009 (Lichtfouse et al., 2015) Climate change is attributed to human activities that have increased global CO_2 content in the atmosphere. The impacts of climate change are evident on a global scale. There are also many major sources of gas emissions especially in industry, energy consumption and transport. This has fuelled interest in studying the capacity of carbon regulation in forests and other terrestrial and wetland ecosystems. One of the elements in blue carbon studies in soil organic carbon (SOC), which is an essential part of soil physical and chemical properties (Jobbágy and Jackson, 2001; Deng et al., 2013). In addition, it is a key element in the process of trapping atmospheric CO_2 in terrestrial ecosystems through primary production (Deng et al., 2013). Wetlands play a key role as suppliers of environmental services, with carbon sequestration being the most important service (Donato et al., 2011). Reservoirs of SOC can act as sources or sinks of atmospheric CO_2, depending on land use practices, climate texture and topography (Cerón-Bretón et al., 2011). Forestry activities such as tree-planting can sequester carbon from the atmosphere, creating a carbon sink, although forest itself is a potential as a carbon source (Hemati et al., 2015; Phang et al., 2015). Uniquely, forestry practices are a serious part of the climate change problem and a key part of the solution. Trees absorb CO_2 from the atmosphere during photosynthesis and store carbon in their stems, branches and roots, which also transfer carbon to the soil (Ashman and Puri, 2002).

Globally, there has been an increasing number of carbon study with

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respect to climate change mitigation, especially in mangrove ecosystems. A recent study evaluating the carbon stocks at different mangrove age stands in South China found that the soil carbon stock increased with age (Guangcheng et al., 2018). Similarly, Adame et al. (2018) discovered almost three-fold of soil carbon stock in Matang Mangrove, Malaysia ranging from 385.2–545.0 t ha^{-1}. Phang et al. (2015) studied a wide range of ecosystems in intertidal habitats in Singapore, concluded that vegetated mangrove ecosystem played an important role in carbon stock and promoted the importance of un-vegetated intertidal habitats to play a similar role in storing the carbon in their sediment.

Mangrove forests account for about 2.4% of tropical forests, and to improve accuracy of global carbon sink estimates, quantification of carbon dynamics is essential (Chmura et al., 2003). So far in Malaysian mangrove, carbon stock has only been reported in shallow depth (Chai Hong et al., 2017) and in production forest (Adame et al., 2018). Therefore, the aim of this study was to quantify ecosystem carbon stocks (also sometimes referred to as carbon density) in different mangrove forests in relation to ecological distribution and community structure. Specific objectives were to assess and compare the carbon stock in the sediment and vegetation of Delta Kelantan and Johor Park mangrove forests at different seasons (wet, dry and intermediate) and also to estimate potential CO_2 emissions or CO_2 equivalent in ecosystem loss. Therefore, the results from this study were expected to increase knowledge on mangrove stand structure and carbon content, to benefit relevant government agencies for mangrove forest management and to encourage public awareness towards mangrove conservation.

2. Materials and methods

2.1. Study sites

Two sites were chosen for the purpose of this study: Delta Kelantan (DK) and Johor Park (JP). DK is located in the district of Tumpat, the state of Kelantan, on the northeast coast of Peninsular Malaysia. Kelantan River is the main river running through the delta, which debouches into the South China Sea. This large delta was developed by the river with sand spits and sand bars common at the river mouth, and there are 17 islands surrounding the delta. Fig. 1 shows the aerial view of two chosen stations: Che Minah Island (6°12′44.38″ N, 102°09′53.84″ E) and Terendak Island (6°12′47.23″ N, 102°10′13.07″ E). DK was chosen because of its deltaic setting and its location on the northeast coast of Peninsular Malaysia. Kelantan's climate is influenced by the northeast and southeast monsoons that blow from late November to March and from June to September, respectively. In 2015, the estimated total amount of rainfall was 2647 mm per annum with heavy rainfall during the northeast monsoon. The temperature ranged from 22.7 °C to 32.9 °C with an estimated mean of 26.8 °C. The humidity of the region was estimated to be about 83.7% (Malaysia Meteorological Department, 2015).

Johor is the southernmost state in Peninsular Malaysia where three Ramsar Sites, i.e., Pulau Kukup, Tanjung Piai and Sungai Pulai Forest Reserves, are located (Fig. 1). These sites are also designated as part of JP. According to Wetland International Malaysia (2009), Johor holds 28.7% of mangrove forests in Peninsular Malaysia (27,733 ha). In this study, two stations were chosen: Tanjung Piai (01°16.00′N 103°30.46′E) and Pulau Kukup (1°18′60.00″ N, 103°26′59.99″ E), which are covered with about 1173.2 ha of mangroves (Tan et al., 2012). Fig. 1 shows Pulau Kukup, a mangrove island, and Tanjung Piai, a coastal mangrove area. The mangroves in Tanjung Piai and Pulau Kukup are dominated by *Rhizophora apiculata* as the most common species, followed by *Bruguiera cylindrica* and *Ceriops tagal* (Tan et al., 2012). These stations were chosen because their location meets the narrow Straits of Malacca, which is one of the busiest straits in the world. In 2012, the total amount of rainfall in this area was about 2104.1 mm and the air temperature was between 26.0 and 29.5 °C (Nordatul Akmar and Wan Juliana 2012).

2.2. Sampling frequency

Samples were collected once during each of three seasons: in June–July (dry season), December (wet season) and February–March (intermediate season). Data collected at the two stations in each site, was pooled to yield datasets representing the respective study sites, i.e. DK and JP.

2.3. Forest inventory

The inventory unit was divided into six circular plots with a radius of 6 m for every sampling area in DK. At each plot, inventory data such as species composition and diameter at breast height (DBH) were recorded. DBH was measured at 1.37 m above the ground, and for stilt-rooted species like *Rhizophora* spp., stem diameter was measured above the highest stilt root (Komiyama et al., 2005). Forest inventories conducted by Tan et al. (2012) in Pulau Kukup and Tanjung Piai were referenced to calculate biomass at the Johor sites.

2.4. Biomass calculation of vegetation

Tree biomass is defined as the total amount of living organic matter in trees and is expressed as oven-dry biomass per unit area (t ha^{-1}). Measurements of DBH can be used to calculate aboveground biomass (AGB) using allometric relationships between DBH and the biomass of individual plant parts. Allometric equations adapted from Komiyama et al. (2005) were used to estimate AGB and belowground biomass (BGB). Komiyama et al. (2005) was chosen because they sampled Southeast Asian mangroves when developing the equations, and favoured by many researchers as it doesn't require height data. However, since no geomorphic context was considered, the results presented hereafter ought to be treated with caution because Saintilan (1997) had proven that biomass allocation between above and below-ground parts within the same species varied with salinity. Adame et al. (2017) suggested the use of species-specific equations to minimize the error.

For *Avicennia marina* and *Bruguiera cylindrica*:

$$AGB = 0.251\ \rho\ D^{2.46} \text{and } BGB = 0.199\ \rho^{0.899} D^{2.22}$$

For *R. apiculata* and *R. mucronata*:

$$AGB = 0.1709\ \rho\ D^{2.516} \text{and } BGB = 0.199\ \rho^{0.899} D^{2.22}$$

where D = DBH of the species in cm, and ρ = wood density of tree trunk (g cm^{-3}).

2.5. Vegetation sampling

Dominant mangrove species in DK were *A. marina* and *R. apiculata*, whereas dominant species in JP were *R. mucronata* and *B. cylindrica*. Sampled trees were divided into their respective parts: leaf, branch, stem, bark (aboveground) and root (belowground). Leaf, branch and root samples were collected and stored in sealed plastic bags for further processing in the laboratory. A sharp knife was used to scrape bark samples off trees, while stem samples (the secondary layer of the wood) were collected using a cordless hammer drill. Three replicates per plant part were obtained for each of the mangrove species present. In total, 360 samples of vegetation parts were collected. The respective samples were weighed and oven-dried for 3–4 days at 80 °C to remove the remaining moisture content. The dried samples were weighed again and finely ground into clay-sized particles using a 1-Liter Laboratory Blender (7009L/7009G) with SS110 Pulverizer Stainless Steel Container. The carbon content of the samples was then determined using the Walkley-Black chromic acid wet oxidation method (Walkley and Black, 1934).

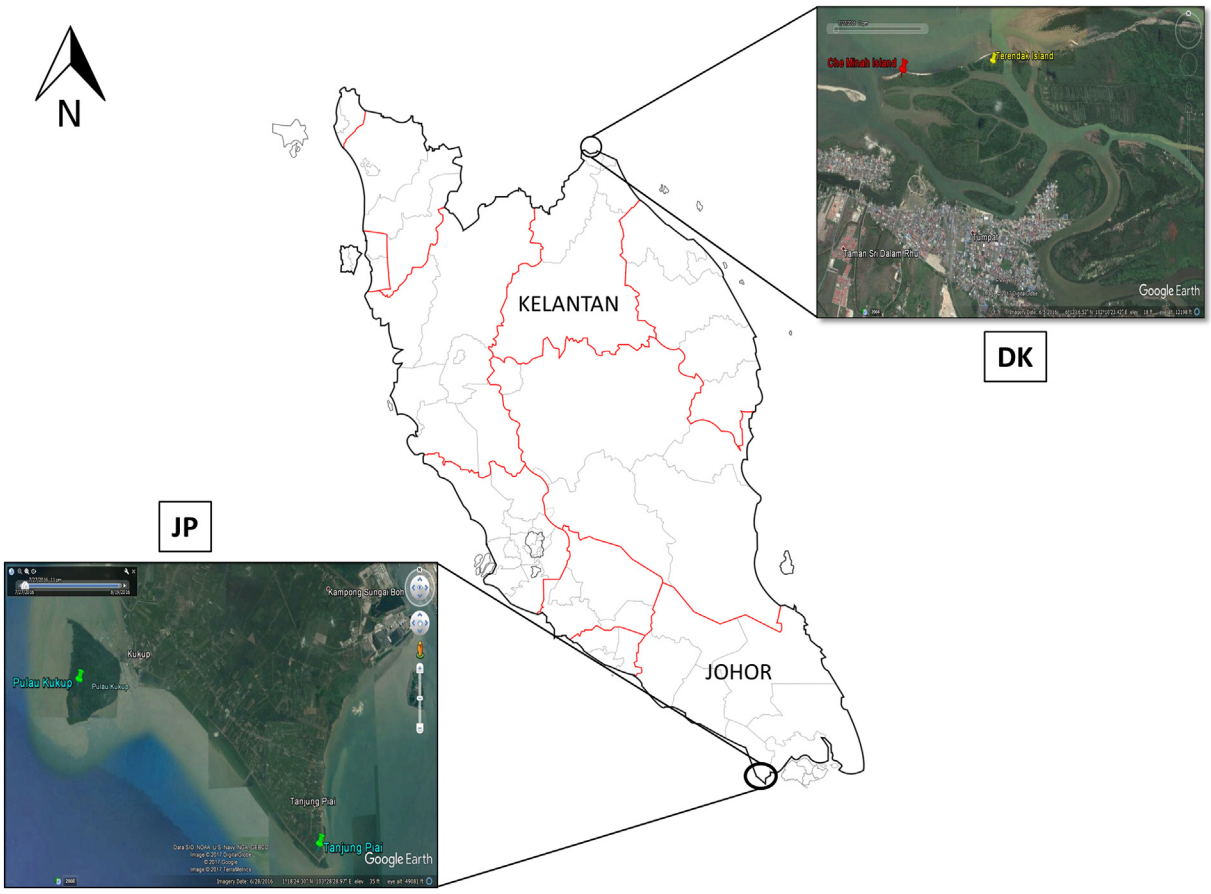

Fig. 1. Map of Peninsular Malaysia showing both study sites.

2.6. Sediment sampling

Transects were established based on visual inspection of sampling sites after locating the three sampling points in each station. Samples were taken from 0 to 20, 20–40, 40–60, 60–80 and 80–100 cm depths using an Eijkelkamp multi sampler. Each partition was carefully placed in separate sealed bags for protection and preservation. In the laboratory, the soil samples were air-dried at ambient temperature for two weeks until completely dry. Then the samples were pulverized into a fine powder using a 1-Liter Laboratory Blender (7009L/7009G) with SS110 Pulverizer Stainless Steel Container. Each partition was analyzed for texture determination (Particle Size Analyser, Beckman Coulter (LS 13, 320)), bulk density and organic carbon content. Soil texture was determined through three soil constituents, which were clay, silt and sand. The organic carbon was also quantified by using the Walkley-Black chromic acid wet oxidation method (Walkley and Black, 1934). The pH and salinity of sea water were also measured using a multiprobe (Hanna Instruments, Italy, model HI 9829-02042).

2.7. Bulk density

Soil sampling for bulk density and carbon analysis requires getting undisturbed soil samples. Samples collected from 0 to 20, 20–40, 40–60, 60–80 and 80–100 cm soil depths were oven-dried to a constant mass at 105 °C. Bulk density was determined by dividing the mass of the oven-dried soil sample by the volume of the sample (Black, 1965):

$$\text{Soil bulk density (g cm}^{-3}) = \frac{\text{Oven-dried sample mass (g)}}{\text{Sample Volume (m}^3)}$$

2.8. Calculating soil carbon pools

Summing the mass of each sampled soil depth can determine the total soil carbon pools. So the total carbon pool was determined by partitioning the soil horizon into depth intervals of 0–20, 20–40, 40–60, 60–80 and 80–100 cm, and taking measurements of bulk density and carbon concentration for each layer.

Soil carbon mass per sampled depth interval was calculated as follows (Kauffman et al., 2011):

$$\textbf{Soil carbon}\ (\text{t ha}^{-1}) = \text{bulk density (g cm}^{-1}) \text{ x soil depth interval (cm) x\% C,}$$

where %C is the carbon concentration expressed as a whole number.

2.9. Total carbon stock

The total carbon stock or pool was estimated by adding all of the component pools. First, each component pool was averaged across all plots (trees and soil). Then these average values were then summed to obtain the total.

The equation for total carbon stock or pool was as follows (adapted from Kauffman and Donato 2012):

$$\textbf{Total carbon stock}(\text{t ha}^{-1}) \text{ of the sampled stand} = C_{treeAG} + C_{treeBG} + C_{soil};$$

where C_{treeAG} = aboveground carbon stock, C_{treeBG} = belowground carbon stock, C_{soil} = soil carbon stock.

2.10. Carbon dioxide equivalents

Greenhouse gas inventories (and emissions) are often reported in units of CO_2 equivalents, or CO_2e. This convention is because CO_2 is the most common greenhouse gas form of carbon. Total carbon density or total carbon stock was converted to CO_2e by multiplying carbon stock by 3.67 (after Kauffman and Donato 2012).

2.11. Statistical analysis

For each study site, descriptive, comparative and relational statistical analyses were performed for carbon storage rate, site, soil depth and climatic period. Mean values were obtained for the different depths, and two-way ANOVA was performed to determine if there were statistically significant differences between the sites. The data was categorized based on locations and seasons. IBM SPSS Statistics version 21 was used to analyse all the data in this study.

3. Result

3.1. Forest inventory and biomass

Avicennia marina and *R. apiculata* were the only species found in both stations in DK. Tan et al. (2012) recorded 16 species in both stations in Johor but *R. mucronata* and *B. cylindrica* were chosen for carbon determination based on their dominance and availability. Tree density in DK ranged from 885 to 1445 trees/ha, while tree density in JP was much higher at 1530–2590 trees/ha (Tan et al., 2012). At DK, the largest tree was an *A. marina* tree with a DBH of 96 cm, while mean DBH of the trees in that site was 47 ± 23 cm. AGB and BGB for *A. marina* was calculated as 112 and 44 t ha^{-1}, respectively. The smaller *R. apiculata* trees had AGB and BGB values of 44.16 and 18.00 t ha^{-1}, respectively. At JP, the trees were much smaller (mean DBH = 11.2 ± 0.3 cm, max DBH = 31.6 cm). AGB and BGB for *R. mucronata* was 36.83 and 18.88 t ha^{-1}, respectively. For *B. cylindrica*, AGB and BGB was 33.34 and 16.02 t ha^{-1}, respectively.

3.2. Vegetation carbon composition, distribution and stock

3.2.1. Carbon in mangrove vegetation

Although both study sites had different dominant species, mean carbon content of vegetation was not significantly different ($p > 0.05$). At DK organic carbon content of *A. marina* was greater than that of *R. apiculata*, and mean organic carbon was 44.90 ± 9.13%. In JP, organic carbon content of *R. mucronata* was greater than *B. cylindrica,* and mean organic carbon was 48.07 ± 7.68%. While organic carbon was highest during the intermediate season in DK (50.17 ± 9.47%) and the dry season in JP (53.55 ± 6.27%), aboveground carbon was not significantly influenced by season.

For both sites, the stem component contained the most carbon, while the lowest proportion of carbon was found for the leaf component in JP and root component in DK and the difference was not significant (Fig. 2). For both sites, mean organic carbon content of AGB was significantly higher than that of BGB (Fig. 3).

3.2.2. Vegetation biomass and carbon stock

For both DK and JP, vegetation biomass was proportional to carbon stock (Table 1). Although DK and JP recorded not significantly different in vegetation carbon stock values, mean organic carbon stored in vegetation across seasons was far lower for JP (50.68 t ha^{-1}C) than for DK (99.18 t ha^{-1}C).

3.3. Soil analysis

3.3.1. Soil texture, pH and salinity

At DK, there was a significantly greater percentage of sand than silt and clay ($p = 0.00$; Fig. 4). Soil texture analysis showed that the soil here was sandy loam. At JP, the percentage of silt was significantly greater than that of clay and sand (p = 0.00). Soil texture analysis showed that silty loam was the soil type at this site.

There was a significant difference in pH values across seasons and between sites ($p = 0.00$). Soil pH at JP was slightly basic (pH = 8.5 ± 0.2), and at Kelantan was slightly acidic (pH = 6.65 ± 0.3). There was no significant difference in salinity across seasons and between sites ($p = 0.117$; Table 2). Salinity was high during the dry season at both sites, and higher at JP than at DK, across seasons.

3.3.2. Soil carbon

Mean organic carbon of the soil in DK (413.33 t ha^{-1} C) was significantly higher than that in JP (384.57 t ha^{-1} C; $p < 0.05$) as shown in Table 3. In JP, soil carbon tended to increase from the wet to the dry season while the opposite was observed for DK. It is worth noting that dry season recorded very low carbon concentration in DK, although in average DK has a higher soil carbon concentration.

3.3.3. Soil depth

SOC concentration increased with depth at DK, with the uppermost layer (10–20 cm) having the lowest organic carbon content, but no significant difference in organic carbon was found among the soil layers at either site ($p = 0.249$; Fig. 5). The highest carbon concentration was found at the 80–100 cm layer in both DK and JP.

3.4. Ecosystem carbon pool and carbon dioxide equivalent

The total carbon stock in JP was 427.88 t ha^{-1}, and 512.51 t ha^{-1} in DK, with soil carbon making up 89% of that total in JP and 80% in DK (Fig. 6). The CO_2 equivalent for JP was 1570.32 t ha^{-1} CO_2e and for DK was 1880.91 t ha^{-1} CO_2e.

4. Discussion

Our results revealed that while fewer species were recorded in DK than in JP, DK supported larger mangrove trees than JP. Soil texture exerts a major influence on species composition in mangroves—while Avicenniaceae thrive in sandy soil, Rhizophoraceae prefers silty soil (Tomlinson, 1986). Satyanarayana et al. (2010) found that the number and distribution of mangrove species in DK was influenced by environmental parameters such as depth, turbidity, temperature, salinity, pH and dissolved oxygen.

Although tree density was higher in JP, individual tree size as measured in DBH was higher at DK, and this reflected in biomass value. However, the variation in AGB may also be influenced by local climatic conditions such as temperature, solar radiation, rain and frequency of storms, as well as soil properties and nutrient status (Komiyama et al., 2008). While values obtained in the present study are low, these values are still within the reported ranges reviewed by Komiyama et al. (2008). Komiyama et al. (2008) attributed the differences in biomass as a gradient factor where biomass increases inland from near the sea but the present study did not support this view. Komiyama et al. (2008) added that environmental factors such as soil properties and nutrient status may also affect mangrove biomass.

The present study revealed differences in soil type of the mangrove forests in DK and JP—the former is sandy whereas the latter is silty. According to Silver et al. (2000), sandy soil stores more carbon than clay soil and in this study DK significantly contained higher carbon stock compared to JP. The presence of parent trees in both DK and JP also helped to maintain the soil type and stabilize the soil constituents, as suggested by Ellison et al. (2000).

The higher salinity recorded for JP compared to DK (although not significant) could be due to the proximity of the former to the sea and influx of sea water, whereas the delta at DK is a buffer from the

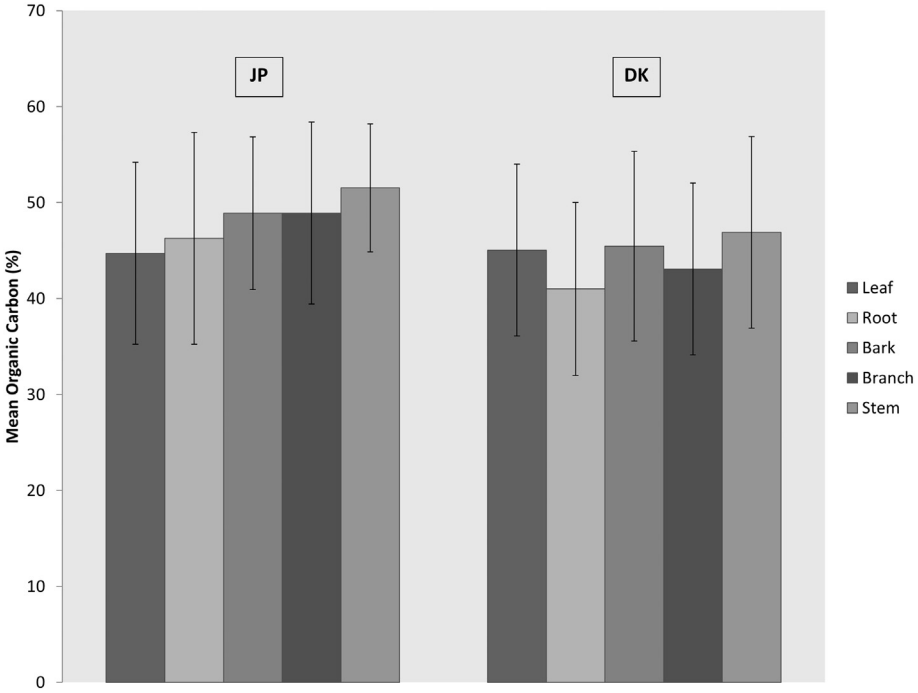

Fig. 2. Mean organic carbon concentration in various parts of vegetation.

influence of seawater, with freshwater influx diluting seawater (Rajasegar, 2003). The higher acidity in JP could be attributed to anaerobic condition as well as microbial and faunal activity in the soil (Li et al., 2009). Both sites ranged from 11 to 16 ppt in salinity, favorable for *Rhizophora* spp. growth which is supported by the study by Kathiresan and Bingham (2001). While Joshi and Ghose (2014) found *A. marina* growth is optimum in a higher salinity range of 18.4 to 21 ppt. Saintilan (1997) reported a significant negative correlation between salinity and belowground biomass, which coincide with the present finding. The currrent study used the standard Komiyama et al. (2005) allometric equations for estimating above and belowground biomass for the reasons stated earlier. Although the aboveground biomass may not be as critical, belowground biomass may create uncertainty due to unique soil condition especially salinity. Furthermore, Adame et al. (2017) discovered that allometric equation method provided root biomass values that were 40% larger than those obtained from field measurements with cores. Hence, the result obtained in this study might be overestimated, although we have tried to minimize the error by using species-specific equations.

The proportionally larger carbon stock held by stems and bark in the present study concurs with previous reports (e.g., Lugo and Snedaker, 1974; Ong et al., 1995; Komiyama et al., 1988) that stems and branches

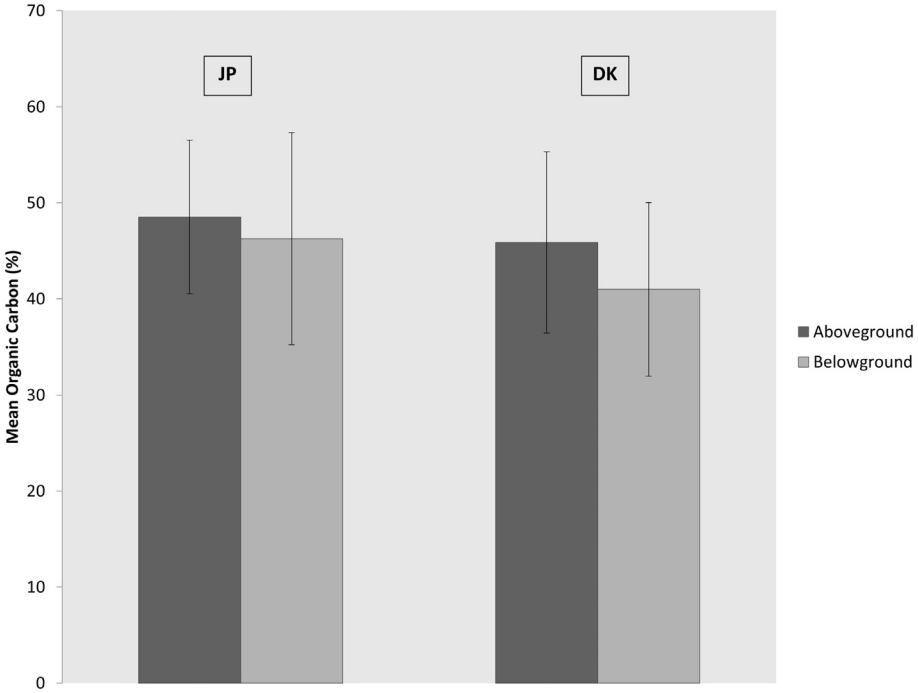

Fig. 3. Mean organic carbon concentration in above and below ground vegetation.

Table 1
Vegetation biomass and carbon stock of mangrove forest in DK and JP across 3 seasons.

	Species	Wood Carbon Content (%value ± sd)	Aboveground Biomass (t ha^{-1})	Aboveground Organic Carbon Content (t ha^{-1})[a]	Root Carbon Content (%value ± sd)	Belowground Biomass (t ha^{-1})	Belowground Organic Carbon Content (t ha^{-1})[b]	Total aboveground and belowground carbon stock (t ha^{-1})
DK								
Dry	*R. apiculata*	37.57 ± 5.65	44.16	16.60	37.34 ± 3.94	18	6.72	
	A. marina	43.35 ± 3.73	112.19	48.63	31.04 ± 6.75	44.64	13.86	
Total				65.23			20.58	
Wet	*R. apiculata*	42.54 ± 9.21	44.16	18.79	40.53 ± 4.73	18	7.30	
	A. marina	47.84 ± 8.40	112.19	53.67	43.85 ± 9.48	44.64	19.57	
Total				72.46			26.87	
Intermediate	*R. apiculata*	53.09 ± 8.99	44.16	23.44	49.15 ± 9.60	18	8.85	
	A. marina	55.18 ± 5.85	112.19	61.91	44.10 ± 8.31	44.64	19.69	
Total				85.35			28.54	
MeanTotal			156.35	73.05 ± 10.19		62.64	26.13 ± 4.20	99.18
JP								
Dry	*R. mucronata*	54.94 ± 3.67	36.83	20.23	55.35 ± 5.45	18.88	10.45	
	B. cylindrica	53.67 ± 3.61	33.34	17.90	57.85 ± 2.78	16.02	9.27	
Total				38.12			19.72	
Wet	*R. mucronata*	41.94 ± 3.09	36.83	15.45	39.78 ± 3.23	18.88	7.51	
	B. cylindrica	53.03 ± 11.70	33.34	17.68	43.43 ± 11.32	16.02	6.96	
Total				33.13			14.47	
Intermediate	*R. mucronata*	52.41 ± 5.54	36.83	19.30	48.35 ± 6.31	18.88	9.13	
	B. cylindrica	46.37 ± 4.20	33.34	15.46	32.85 ± 9.83	16.02	5.26	
Total				34.76			14.39	
MeanTotal			70.169	35.43 ± 2.54		34.90	15.25 ± 3.05	50.68

[a] Aboveground vegetation carbon content were determined as the product of vegetation aboveground biomass multiplied by wood carbon content (%) obtained by the mean carbon of stem and bark, following Kauffman et al. (2011).

[b] The belowground vegetation carbon content were calculated as the product of vegetation belowground biomass multiplied by root mean carbon content (%), following Kauffman et al. (2011).

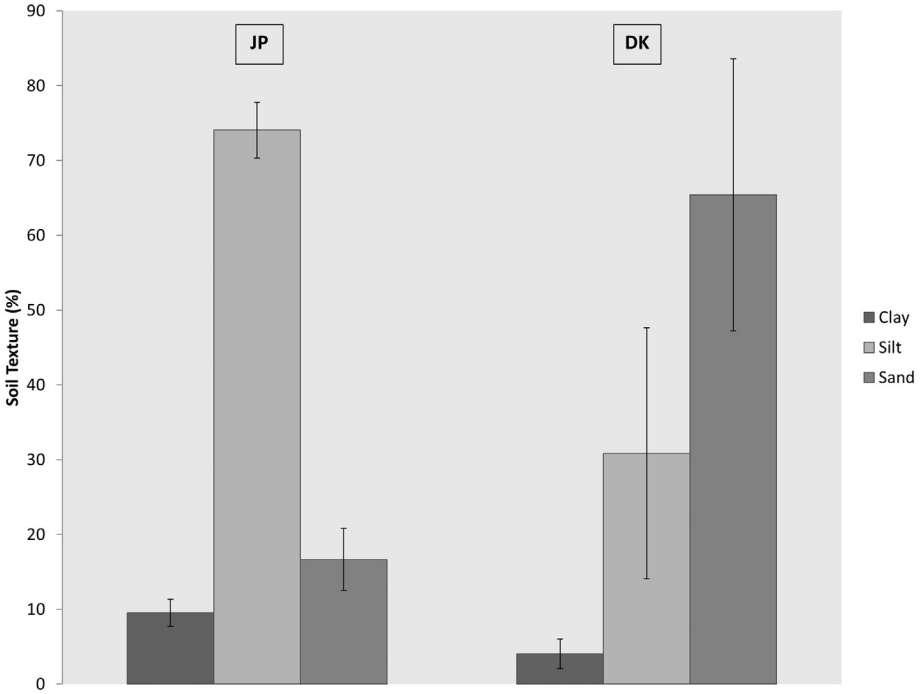

Fig. 4. Soil particle analysis at both study sites.

Table 2
Range of salinity and pH in both sites (mean ± SD).

Season	Wet		Dry		Intermediate		Soil texture
Parameters	pH	Salinity (ppt)	pH	Salinity (ppt)	pH	Salinity (ppt)	
JP	8.30 ± 0.15	14.17 ± 0.41	8.70 ± 0.38	16.00 ± 0.63	8.49 ± 0.24	15.17 ± 1.33	silt loam
DK	6.35 ± 0.10	11.53 ± 0.20	7.03 ± 0.08	11.68 ± 0.43	6.67 ± 0.29	11.68 ± 0.42	sandy loam

Table 3
Soil carbon stock of mangrove forests in DK and JP.

Location	Season	Soil depth (cm)	OC (%)	Bulk Density (g/cm^3)	Soil Carbon Storage (t ha^{-1})[a]	Average Total Soil Carbon Storage (t ha^{-1})
DK	Dry	0-20	1.67	0.74	24.72	
		20-40	1.45	1.06	30.74	
		40-60	1.66	0.95	31.54	
		60-80	1.8	1.08	38.88	
		80-100	1.54	1.09	33.57	
	Total				159.45	
	Wet	0-20	5.63	0.74	83.32	
		20-40	5.14	1.06	108.97	
		40-60	5.10	0.95	96.90	
		60-80	5.58	1.08	120.52	
		80-100	6.82	1.09	148.68	
	Total				558.4	
	Intermediate	0-20	5.56	0.74	82.29	
		20-40	5.60	1.06	118.72	
		40-60	4.60	0.95	87.4	
		60-80	5.10	1.08	110.16	
		80-100	5.53	1.09	120.56	
	Total				519.12	413.33
JP	Dry	0-20	5.1	0.55	56.10	
		20-40	6.97	0.54	75.28	
		40-60	7.25	0.67	97.15	
		60-80	6.35	0.69	87.64	
		80-100	8.9	0.62	110.36	
	Total				426.52	
	Wet	0-20	4.10	0.55	45.10	
		20-40	4.50	0.54	48.60	
		40-60	6.86	0.67	91.92	
		60-80	4.26	0.69	58.80	
		80-100	6.15	0.62	76.26	
	Total				320.68	
	Intermediate	0-20	5.87	0.55	64.57	
		20-40	6.68	0.54	72.14	
		40-60	6.80	0.67	91.12	
		60-80	7.17	0.69	98.94	
		80-100	6.43	0.62	79.74	
	Total				406.51	384.57

[a] The soil carbon storage was determined as the product of mean carbon percentage for each depth multiplied by soil bulk density and the soil depth interval, following Kauffman et al. (2011).

comprise the largest proportion of AGB. Furthermore, Mitra et al. (2011) noted that AGB of certain species is solely due to stem biomass and therefore can be treated as a permanent indicator of biomass production, unlike branches and leaves.

The soil carbon pool is often the largest, and measuring it is important in determining long-term dynamics associated with the climate change and/or land management. Soil carbon pools usually constitute over 50% and sometimes over 90% of the total ecosystem carbon stock of mangroves (Donato et al., 2011; Kauffman et al., 2011), consistent with the current study. Carbon was also found to remain more stable in the soil than in vegetation (Adame and Fry, 2016). The principal factors affecting the determination of soil C stocks are C concentration, bulk density, and the total depth over which estimates are integrated. The C content in the present study is comparable with other studies elsewhere (e.g. Kristensen et al., 2008; Jones et al., 2014 and Donato et al., 2012). C stock in soil is also depending on its bulk density. Data on mangrove soil bulk density is marginal across the literature and seldom discussed in direct correlation to C stock studies. Others have reported mean bulk density values ranging from 0.18 g cm^{-3} (Kauffman et al., 2011) to 1.26 g cm^{-3} (Jones et al., 2014), concurred with the current study. DK soils had higher bulk densities than in JP and this could be due to the sandy soil texture in DK versus the silty soil texture in JP. Therefore, soil bulk density positively correlates with carbon stock, and can be a useful criterion to facilitate inter-study comparisons. However, the tools can also obscure differences in soil characteristics, as extremes in the two input parameters that determine C density can often offset each other to produce similar values.

Mangroves soils are usually anaerobic, with low decomposition rates, which produce favorable conditions for the preservation of organic carbon (Matsui, 1998). It was also observed that SOC was higher in Johor during the dry season than during other seasons likely because the accumulation of organic matter increases during the dry season. However, the decomposition rate is high and this trend continued until the intermediate season. In contrast, SOC in DK was significantly higher during the wet season as compared with other seasons. This was expected since DK receives nutrients from the mainland flowing to the delta during the wet season. Seasons clearly played a major role in carbon stock variation in DK where the lowest carbon stock was found in the dry season, contrary to studies by Cerón-Bretón et al. (2011) and Raza et al. (2011), which concluded the highest SOC content was during the dry season.

Both JP and DK recorded comparable ecosystem carbon stocks than were reported for mangroves in other studies (e.g. Kauffman et al., 2011; Phang et al., 2015; Adame et al., 2015; Hossain, 2014). The differences in the carbon stock calculated in the present study could be attributed to the differences in determining carbon content and also the partitions used to represent ecosystem carbon stock. The current study sampled living vegetation and soil up to 1 m depth and did not take into account carbon contributed by litter and downed wood.

Initial published estimates for the amount of C released from Indo-Pacific mangroves with land-use change range from 400 to 1400 t ha^{-1} CO_2e cleared, depending on the severity of disturbance (Donato et al., 2011). The carbon emissions in JP and DK were estimated at 1570 and 1880 t ha^{-1} CO_2e, respectively, comparable with those in other regions such as Yap (Federated States of Micronesia), Babeldaob (Republic of Palau), the Sundarbans, Bangladesh and Kalimantan, Indonesia, as reported by Donato et al. (2012).

Although DK is a fishing village with free access to the forest, the carbon stock was higher than that in JP. However, as a designated Ramsar site, JP has potential to sequester carbon. Fortunately, logging is not permitted in either site. Due to their unique locations by the coast where carbon sources in these mangroves could be either allocthonous or autochtonous, the mangroves in Johor and Kelantan are important sites for global carbon budget (Alongi, 2008). Restoration of mangroves can increase carbon stock and likewise their removal may remove a large amount of carbon (Lovelock et al., 2011) and SOC loss from the conversion of natural cultivated vegetation is well documented (Yan et al., 2012). The present study provides valuable information that mangrove forest is crucial in sequester carbon and reduce carbon emissions.

5. Conclusion

This study showed that both sites possessed different mangrove species, yet the carbon allocation within vegetation parts was similar, although both sites showed different soil carbon concentration. Autochtonous materials such as mangrove-derived roots and detritus are the main contributors of significant amounts of organic carbon to the sediment in both study sites. This study generally concluded that seasonal change would not affect the mangrove trees in terms of their capacity for carbon sequestration, but sedimentation may be affected by decomposition and decay on the forest floor, and organic carbon content could fluctuate as driven by seasonal changes. This study demonstrates that biomass and carbon storage capacity in mangrove forests vary with location due to varying salinity, soil texture and water flow. Overall, this baseline study for DK and JP has the potential to

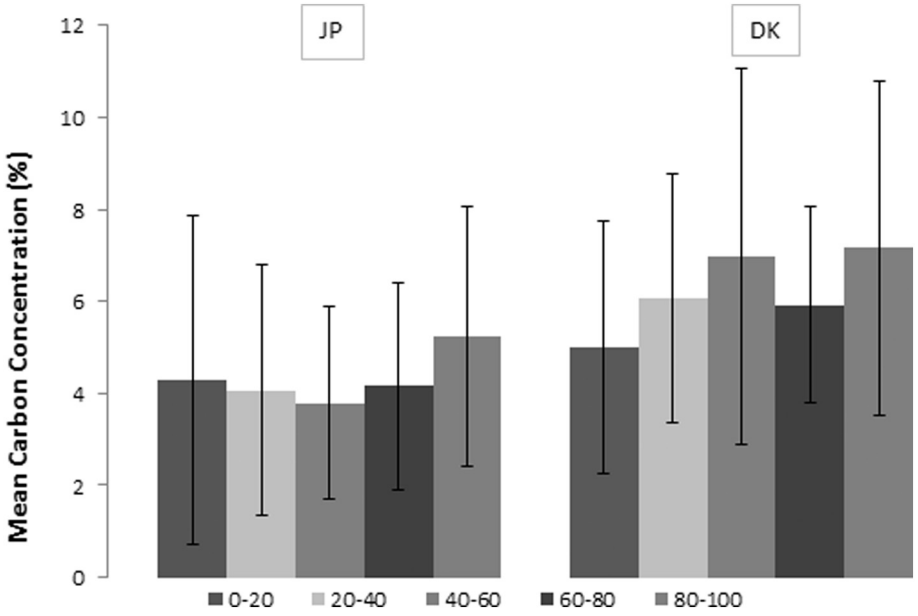

Fig. 5. Mean carbon concentration at interval depths in soil samples.

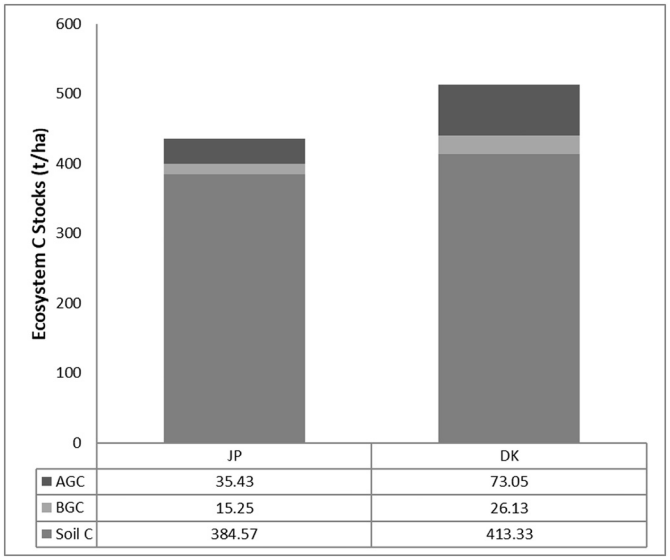

Fig. 6. Distribution of carbon stock allocation between aboveground, belowground and soil.

become a blueprint for future blue carbon projects in this region.

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References

Adame, M.F., Fry, B., 2016. Source and stability of soil carbon in mangrove and freshwater wetlands of the Mexican Pacific coast. Wetl. Ecol. Manag. 24 (2), 129–137.
Adame, M.F., Santini, N.S., Tovilla, C., Vázquez-Lule, A., Castro, L., Guevara, M., 2015. Carbon stocks and soil sequestration rates of tropical riverine wetlands. Biogeosciences 12 (12), 3805–3818.
Adame, M.F., Cherian, Sam, Reef, Ruth, Stewart-Koster, Ben, 2017. Mangrove root biomass and the uncertainty of belowground carbon estimations. For. Ecol. Manag. 403, 52–60.
Adame, M.F., Zakaria, R.M., Fry, B., Chong, V.C., Then, Y.H.A., Brown, C.J., Lee, S.Y., 2018. Loss and recovery of carbon and nitrogen after mangrove clearing. Ocean Coast. Manag. 161, 117–126.
Alongi, Daniel M., 2008. Mangrove forests: resilience, protection from tsunamis, and responses to global climate change. Estuar. Coast. Shelf Sci. 76 (1), 1–13.
Ashman, M.R., Puri, G., 2002. Essential Soil Science: A Clear and Concise Introduction to Soil Science. Blackwell Science, Oxford.
Black, C.A., 1965. Methods of Soil Analysis. Part 1. American Society of Agronomy (No 9).
Cerón-Bretón, J.G., Cerón-Bretón, R.M., Rangel-Marrón, M., Murielgarcia, M., Cordova-Quiroz, A.V., Estrella-Cahuich, A., 2011. Determination of carbon sequestration rate in soil of a mangrove forest in Campeche, Mexico. WSEAS Transactions on Environment and Development 7 (2), 55–64.
Chai Hong, Liu, Hemati, Zhila, Zakaria, Rozainah M., 2017. Carbon stock evaluation of selected mangrove forests in Peninsular Malaysia and its potential market value. Journal of Environmental Science and Management 20 (2), 77–87.
Chmura, Gail L., Anisfeld, Shimon C., Cahoon, Donald R., Lynch, James C., 2003. Global carbon sequestration in tidal, saline wetland soils. Glob. Biogeochem. Cycles 17 (4), 1111.
Deng, Lei, Wang, Kai-Bo, Chen, Mei-Ling, Shangguan, Zhou-Ping, Sweeney, Sandra, 2013. Soil organic carbon storage capacity positively related to forest succession on the Loess Plateau, China. Catena 1–7.
Donato, Daniel C., Kauffman, J. Boone, Murdiyarso, Daniel, Kurnianto, Sofyan, Stidham, Melanie, Kanninen, Markku, 2011. Mangroves among the most carbon-rich forests in the tropics. Nat. Geosci. 4 (5), 293–297.
Donato, Daniel C., Boone Kauffman, J., Af Mackenzie, R., Ainsworth, A., Pfleeger, A.Z., 2012. Whole-island carbon stocks in the tropical Pacific: implications for mangrove conservation and upland restoration. J. Environ. Manag. 97, 89–96.
Ellison, Aaron M., Mukherjee, Barid B., Karim, Ansarul, 2000. Testing patterns of zonation in mangroves: scale dependence and environmental correlates in the Sundarbans of Bangladesh. J. Ecol. 88 (5), 813–824.
Giesen, Wulffrat S., Zieren, M., Scholten, L., 2007. Mangrove guidebook for Southeast Asia (ISBN: 974-7946-85-8). Food and Agriculture Organisation and Wetlands International, Bangkok.
Giri, C., Ochieng, E., Tieszen, L.L., Zhu, Z., Singh, A., Loveland, T., Masek, J., Duke, N., 2011. Status and distribution of mangrove forests of the world using earth observation satellite data. Glob. Ecol. Biogeogr. 20 (1), 154–159.
Guangcheng, Chen, Gao, Min, Pang, Bopeng, Chen, Shunyang, Ye, Yong, 2018. Top-meter soil organic carbon stocks and sources in restored mangrove forests of different ages. For. Ecol. Manag. 422, 87–94.
Hemati, Zhila, Hossain, Mahmood, Emenike, Chijioke U., Rozainah, Mohamad Zakaria, 2015. Rate of carbon storage in soil of natural and degraded mangrove forest in Peninsular Malaysia. CLEAN – Soil, Air, Water 43 (4), 614–619.
Herr, D., Pidgeon, E., Laffoley, D. (Eds.), 2012. Blue Carbon Policy Framework: Based on the discussion of the International Blue Carbon Policy Working Group. IUCN and Arlington, USA, Gland, Switzerland.
Hossain, Mahmood, 2014. Carbon pools and fluxes in *Bruguiera parviflora* dominated naturally growing mangrove forest of Peninsular Malaysia. Wetl. Ecol. Manag. 22 (1), 15–23.
Jobbágy, Esteban G., Jackson, Robert B., 2001. The distribution of soil nutrients with depth: global patterns and the imprint of plants. Biogeochemistry 53 (1), 51–77.
Jones, Trevor G., Ratsimba, Harifidy Rakoto, Ravaoarinorotsihoarana, Lalao, Cripps, Garth, Bey, Adia, 2014. Ecological variability and carbon stock estimates of

mangrove ecosystems in northwestern Madagascar. Forests 5 (1), 177–205.
Joshi, Hema Gupta, Ghose, M., 2014. Community structure, species diversity, and aboveground biomass of the Sundarbans mangrove swamps. Trop. Ecol. 55 (3), 283–303.
Kathiresan, K., Bingham, Brian L., 2001. Biology of mangroves and mangrove ecosystems. Adv. Mar. Biol. 40, 81–251.
Kauffman, J. Boone, Heider, Chris, Cole, Thomas G., Dwire, Kathleen A., Donato, Daniel C., 2011. Ecosystem carbon stocks of Micronesian Mangrove Forests. Wetlands 31 (2), 343–352.
Komiyama, Akira, Moriya, H., Prawiroatmodjo, S., Toma, T., Ogina, K., 1988. Forest primary productivity. In: Ogina, K., Chihara, M. (Eds.), Biological Systems of Mangrove. Ehime University, pp. 97–117.
Komiyama, Akira, Poungparn, Sasitorn, Kato, Shogo, 2005. Common allometric equations for estimating the tree weight of mangroves. J. Trop. Ecol. 21 (04), 471–477.
Komiyama, Akira, Ong, Jin Eong, Poungparn, Sasitorn, 2008. Allometry, biomass, and productivity of mangrove forests: a review. Aquat. Bot. 89 (2), 128–137.
Kristensen, Erik, Bouillon, Steven, Dittmar, Thorsten, Marchand, Cyril, 2008. Organic carbon dynamics in mangrove ecosystems: a review. Aquat. Bot. 89 (2), 201–219.
Li, Yong-Tao, Becquer, Thierry, Dai, Jun, Quantin, Cécile, Benedetti, Marc F., 2009. Ion activity and distribution of heavy metals in acid mine drainage polluted subtropical soils. Environ. Pollut. 157 (4), 1249–1257.
Lichtfouse, Eric, Schwarzbauer, Jan, Robert, Didier, 2015. Hydrogen Production and Remediation of Carbon and Pollutants. Springer.
Lovelock, Catherine E., Ruess, Roger W., Feller, Ilka C., 2011. CO_2 efflux from cleared mangrove peat. PLoS One 6 (6), e21279.
Lugo, Ariel E., Snedaker, Samuel C., 1974. The ecology of mangroves. Annu. Rev. Ecol. Syst. 5, 39–64.
Malaysia Meteorological Department, 2015. General Climate of Malaysia. Malaysian Meteorological Department.
Matsui, Naohiro, 1998. Estimated stocks of organic carbon in mangrove roots and sediments in Hinchinbrook Channel, Australia. Mangrove Salt Marshes 2 (4), 199–204.
McLeod, Elizabeth, Chmura, Gail L., Bouillon, Steven, Salm, Rodney, Björk, Mats, Duarte, Carlos M., Lovelock, Catherine E., Schlesinger, William H., Silliman, Brian R., 2011. A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. Front. Ecol. Environ. 9 (10), 552–560.
Mitra, Abhijit, Sengupta, Kasturi, Banerjee, Kakoli, 2011. Standing biomass and carbon storage of above-ground structures in dominant mangrove trees in the Sundarbans. For. Ecol. Manag. 261 (7), 1325–1335.
Ong, J.E., Gong, W.K., Wong, C.H., 1995. Structure and productivity of a 20 year-old stand of *Rhizophora apiculata* B1 mangrove forests. J. Biogeogr. 22, 417–427.
Pendleton, Linwood, Donato, Daniel C., Murray, Brian C., Crooks, Stephen, Jenkins, W. Aaron, Sifleet, Samantha, Craft, Christopher, Fourqurean, James W., Kauffman, J. Boone, Marbà, Núria, Megonigal, Patrick, Pidgeon, Emily, Herr, Dorothee, Gordon, David, Baldera, Alexis, 2012. Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. PLoS One 7 (9), e43542.
Phang, Valerie X.H., Chou, L.M., Friess, Daniel A., 2015. Ecosystem carbon stocks across a tropical intertidal habitat mosaic of mangrove forest, seagrass meadow, mudflat and sandbar. Earth Surf. Process. Landf. 40 (10), 1387–1400.
Rajasegar, M., 2003. Physico-chemical characteristics of the Vellar estuary in relation to shrimp farming. J. Environ. Biol. 24 (1), 95–101.
Raza, Muhammad, Zakaria, Mohamad Pauzi, Hashim, Nor Rasidah, 2011. Spatial and temporal variation of organic carbon in mangrove sediment of Rembau–Linggi Estuary, Malaysia. World Appl. Sci. J. 14, 48–54.
Saintilan, N., 1997. Above-and below-ground biomass of mangroves in a sub-tropical estuary. Mar. Freshw. Res. 48 (7), 601–604.
Satyanarayana, Behara, Idris Indra, F., Mohamad Khairul, A., Husain Mohd, L., Shazili Noor, A.M., Dahdouh-Guebas, Farid, 2010. Mangrove species distribution and abundance in relation to local environmental settings: a case-study at Tumpat, Kelantan Delta, east coast of peninsular Malaysia. Bot. Mar. 53 (1), 79–88.
Silver, Whendee L., Neff, Jason, McGroddy, Megan, Veldkamp, Ed, Keller, Michael, Cosme, Raimundo, 2000. Effects of soil texture on belowground carbon and nutrient storage in a Lowland Amazonian Forest Ecosystem. Ecosystems 3 (2), 193–209.
Sinha, P.C., 2005. Sea Level Rise: Due to Global Warming and Climate Variability. University Malaysia Terengganu, Terengganu.
Tan, D.D., Wan Juliana, W.A., Maimon, A., 2012. Community structure and productivity of mangrove forests in two national parks of West Malaysia. The Malaysian Forester 75 (2), 165–176.
Tomlinson, P.B., 1986. The Botany of Mangroves. Cambridge University Press, University of Cambridge.
Walkley, A., Black, I.A., 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil Sci. 37 (1), 29–38.
Wetland International Malaysia, 2009. http://Malaysia.wetlands.org/ (2 Feb 2010).
Yan, Yun, Tian, Jing, Fan, Mingsheng, Zhang, Fusuo, Li, Xiaolin, Christie, Peter, Chen, Haiqing, Lee, Juhwan, Kuzyakov, Yakov, Six, Johan, 2012. Soil organic carbon and total nitrogen in intensively managed arable soils. Agric. Ecosyst. Environ. 150, 102–110.